



# Low-cycle fatigue damage of buckling prone reinforcing bars

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## ABSTRACT

This study summarises the results of an experimental and analytical study carried out to investigate the influence of buckling on low-cycle fatigue life of reinforcing bars. The parameters considered to experimentally investigate the effect of buckling on low-cycle fatigue life of reinforcing bars are the grade (i.e. strength) of the bars, slenderness ratio of the bars and the loading history. The test results indicate that buckling of bars has detrimental effect on their fatigue life; i.e. increase in the slenderness ratio of bars results in substantial reduction of their low-cycle fatigue life. Regression analysis of the experimental data is carried out and fatigue life equations relating the total strain amplitude with the number of strain reversals to failure as a function of buckling parameter (that defines the buckling proneness of reinforcing bars) are proposed. Further, the proposed fatigue model is implemented into finite element analysis program OpenSees for conducting non-linear cyclic analysis of a typical reinforced concrete column. Comparative evaluation of the numerical results suggests that ignoring the effect of buckling on low-cycle fatigue behaviour of reinforcing bars can result in overestimation of the seismic resistance of reinforced concrete structures.

## 1 INTRODUCTION

Reinforced Concrete (RC) structures in seismically active regions are designed to undergo large inelastic deformations in their predefined critical regions i.e. *plastic hinge regions*. During a seismic excitation, the longitudinal reinforcing bars located in these critical regions undergo large inelastic strain reversals (tension and compression) resulting in accumulation of low-cycle fatigue damage in reinforcing bars. Here, low cycle fatigue damage is defined as the premature fracture of the reinforcing bars subjected to high strain amplitude cycles. The accumulation of fatigue damage in reinforcing bars occurs over the lifespan of structure which is a result of series of events that includes minor to major ground shaking (this includes elastic and inelastic strain

reversals) and may result in premature fracture of reinforcing bars. The fatigue failure of bars in RC structures is a limit state that restricts it from performing its intended function and may sometime result in structural collapse. Therefore, several researchers in the past have investigated the low-cycle fatigue behaviour of bare reinforcing bars (Brown and Kunnath 2004; Hawileh et al. 2010; Mander et al. 1994). However, the failure modes observed during the tests on RC structures along with the failure modes observed during the past earthquakes, highlights rebar buckling as one of the critical and common failure mode. Majority of the damaged RC structures had fracture of buckled reinforcing bars. Further, recent tests carried on slender RC walls at the University of Canterbury highlighted that buckling results in premature fracture of reinforcing bars (Dashti et al. 2017; Tripathi et al. 2019). Even though it has been acknowledged in the literature that buckling accelerates fatigue damage accumulation in reinforcing bars (Brown and Kunnath 2004), only few studies have investigated the effect of buckling on low-cycle fatigue life of reinforcing bars (Kashani et al. 2015; Tripathi et al. 2018; Tripathi et al. 2018; Tripathi et al. 2018).

Therefore, in this paper, experimental tests carried out by the authors to quantify the effect of buckling on low-cycle fatigue life of reinforcing bars along with details of the new low-cycle fatigue model is summarised. To investigate the effect of low-cycle fatigue on deformation capacity of a typical RC column, the proposed model is implemented into the finite element analysis program OpenSees and extensive numerical investigations are carried out. Further, the results from the numerical study highlighting the effect of bar buckling and low-cycle fatigue damage on hysteretic response of RC column is reported.

## 2 LOW-CYCLE FATIGUE LIFE OF REINFORCING BARS

### 2.1 Experimental test programme

The effect of buckling on low-cycle fatigue life of reinforcing bars is investigated by conducting low-cycle fatigue tests on bare reinforcing bars. Figure 1 shows the test setup along with typical fracture failure of some of the buckled reinforcing bars. The parameters considered for experimental investigation were the slenderness ratio of bars ( $L/D$ ), yield strength of the reinforcing steel (Grade 300E and 500E) and loading history. Herein, the slenderness ratio of reinforcing bars is defined as the total buckling length of a reinforcing bar inside an RC member divided by the bar diameter, where the bar buckling length is calculated using the stability model proposed by Dhakal and Maekawa (2002). Bars with different slenderness ratio (6, 9, 12 and 15) were subjected to a constant amplitude cyclic strain loading with total strain amplitudes of 1%, 2%, 3% and 4%.



(a) Test setup



(b) Fractured reinforcing bars

*Figure 1: Low-cycle fatigue tests on reinforcing bars*

Figure 2 shows the cyclic response of Grade 300E and 500E reinforcing bars with different slenderness ratios. As it can be inferred from this figure, reinforcing bars with no buckling (slenderness ratio of 6 and below)

exhibited a similar response in tension and compression. However, as the slenderness ratio is increased, the presence of geometric nonlinearity in the system resulted in a significant deterioration of the compression response of bars. In addition to this, reduction in compression capacity of bars, premature buckling of reinforcing bars i.e. buckling of reinforcing bars while carrying tensile strains was also observed. Premature bar buckling was a result of permanent elongation of reinforcing bars that subjected them to large compressive stresses while still carrying tensile strains, thereby making them buckling prone. Bar buckling resulted in a significant reduction of fatigue life of these reinforcing bars, for a given total strain amplitude of 0.02, an increase in slenderness ratio of Grade 300E and 500E reinforcing bars from 6 to 15 resulted in reduction of fatigue life by 72%. Figure 3 shows the change in fatigue life of Grade 300E and 500E reinforcing bars as a function of total strain amplitude with different slenderness ratios. Also, tests were carried out on reinforcing bars subjected to fatigue loading with different mean strain ratios (where the mean strain ratio is defined as ratio of the minimum to the maximum strain applied to the bars). However no strong correlation between the mean strain ratio and fatigue life was found. Hence the results obtained from tests on reinforcing bars subjected to a fatigue loading with a mean strain ratio of -1.0 were used for developing a new low-cycle fatigue model that includes the effect of bar buckling. The experimental program along with the corresponding results are reported elsewhere in more details (Tripathi et al. 2018).

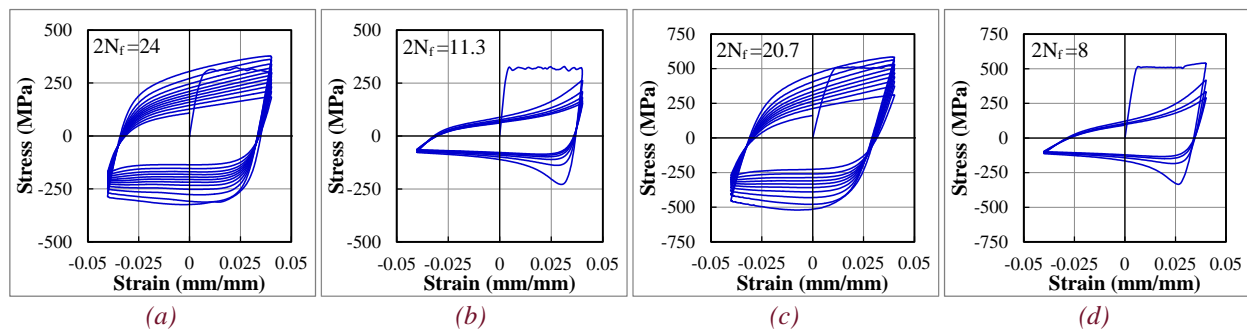


Figure 2: Hysteretic response of reinforcing bars (a)  $L/D=6$ , 300E, (b)  $L/D=15$ , 300E, (c)  $L/D=6$ , 500E, and (d)  $L/D=15$ , 500E (Tripathi et al. 2018)

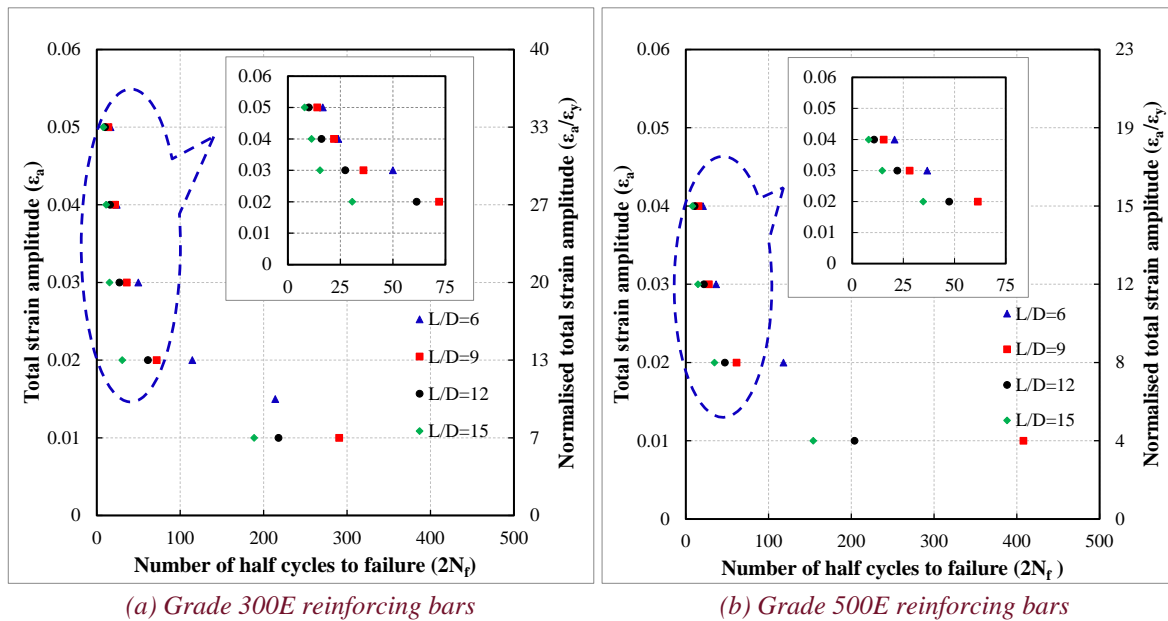


Figure 3: Fatigue life as a function of total strain amplitude for Grade 300E and 500E reinforcing bars (Tripathi et al. 2018)

## 2.2 Low-cycle fatigue model for reinforcing bars

As stated before, most of the fatigue life models developed for reinforcing bars in the literature ignore the detrimental effect of buckling. Therefore, a generic fatigue life model was recently proposed by the authors, which is able to take this effect into account (Tripathi et al. 2018; Tripathi et al. 2018). The traditional strain based fatigue life models are developed based on the generalised fatigue life equation proposed by L. F. Coffin and Schenectady (1954) and Manson (1953), which is represented as:

$$\varepsilon_a = \varepsilon_{\text{elastic}} + \varepsilon_{\text{plastic}} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (1)$$

However, Koh and Stephens (1991), suggested that for most of the fatigue related problems in metals, the plastic strain component remains constant, based on which a simplified fatigue model relating the total strain amplitude with fatigue life of metals was proposed. The fatigue life of a metal based on total strain amplitude can be evaluated as:

$$\varepsilon_a = \beta (2N_f)^a \quad (2)$$

where, ' $\varepsilon_a$ ', ' $\beta$ ', ' $a$ ', and ' $2N_f$ ' are total strain amplitude, fatigue ductility coefficient, fatigue ductility exponent and number of half cycles to failure, respectively. The effect of buckling is incorporated in the fatigue model by calibrating the fatigue life coefficient (' $\beta$ ', ' $a$ ') as a function of buckling parameter ( $\lambda$ ), where the buckling parameter is given by Equation 3 (Dhakal and Maekawa 2002). To achieve this objective, the results obtained from the experimental investigation are consolidated and fitted to a power law function. Regression analysis for each bar type is carried out and an expression relating the fatigue life coefficients with the buckling parameter ( $\lambda$ ) is proposed. The low-cycle fatigue life of reinforcing bars including the ill effects of buckling can be evaluated using Equation 2, where the fatigue life coefficients can be obtained using Equation 4 and Equation 5.

$$\lambda = \frac{L}{D} \sqrt{\frac{f_y}{100}} \quad (3)$$

$$\beta = \frac{-\lambda}{350} + 0.2 \quad (4)$$

$$a = -\left(\frac{\lambda}{1200} + 0.441\right) \quad (5)$$

## 3 NUMERICAL INVESTIGATION ON A TYPICAL RC COLUMN

In order to investigate the effect of the proposed low-cycle fatigue model (that incorporates the effect of buckling) on the seismic performance of RC members, a typical RC column is modelled using OpenSees (Mazzoni et al. 2006). A validated fiber numerical model capable of simulating the cyclic response of flexural members is adopted and parametric studies are carried out on the RC column (Tripathi et al. 2017). In fibre analysis of RC structures, the global response is obtained by integrating the uniaxial behaviour of concrete (confined and unconfined) and steel fibres where the behaviour of uniaxial fibres are defined using path-dependent and cyclic constitutive material models. In this study, the RC column is modelled as a series of displacement-based beam-column elements connected at the nodes (as shown in Figure 4), with the combination of lateral load and axial load being applied at the topmost node. Each element is further discretized

into a number of nonlinear fibre sections along its height that consist of uniaxial confined and unconfined concrete, and steel fibres (as shown in Figure 4c).

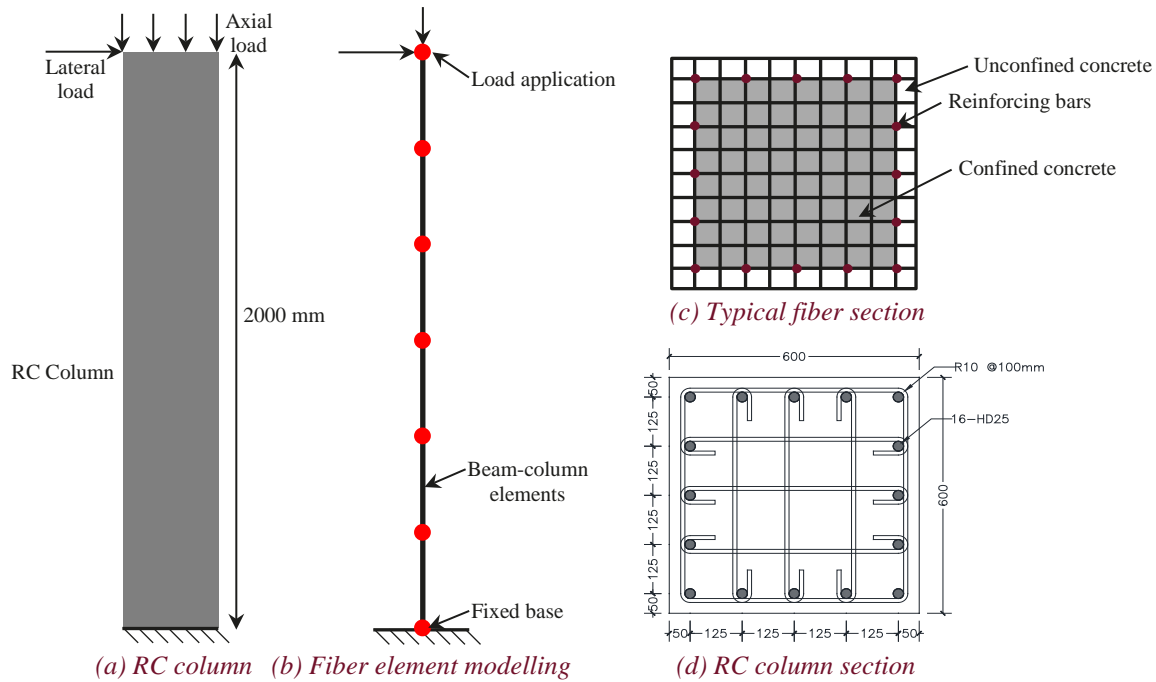


Figure 4: Schematic layout of the fiber element modelling in OpenSees

The nonlinear cyclic response of concrete (confined and unconfined) is simulated using the Concrete02 material model available in OpenSees. The cyclic behaviour of confined concrete is simulated by calibrating the strength and stiffness of Concrete02 material model based on the recommendations proposed by Saatcioglu and Razvi (1992). To facilitate the inclusion of buckling in the numerical analysis, reinforcing bars are modelled using the Hysteretic Material model available in OpenSees. Hysteretic Material model is a generic cyclic material model that consists of two independent envelope functions to define the tension and compression response of any material. Also, the material model facilitates modification of hysteretic rules (i.e. the cyclic loops connecting the envelope functions) using the pinching and damage parameters attached to the material model. In this study, the tensile behaviour of the reinforcing bars is defined using a bilinear stress-strain curve with strain hardening, whereas the compressive response is defined using the buckling model proposed by Dhakal and Maekawa (2002). The pinching parameters for bars with different buckling length were arrived by calibrating the hysteretic material model with the experimental results reported in literature (Tripathi et al. 2018; Tripathi et al. 2018; Tripathi et al. 2018). Although this approach of using a generic hysteretic material model to simulate reinforcement buckling may sometimes exaggerate the buckling induced effects, this method is proven to provide a good estimation of RC columns behaviour (Kashani et al. 2016).

The fatigue induced degradation of reinforcing bars is modelled using the Fatigue Material model available in OpenSees. Fatigue Material model is a generic fatigue model based on the relationship proposed by Coffin and Manson and utilizes the modified rainflow cycle counting algorithm to track the accumulated damage in the steel material. Herein, the fatigue coefficients for reinforcing bars with different slenderness ratios are evaluated using Equation 2 and then implemented in the OpenSees material model. Strictly speaking, based on the stability model proposed by Dhakal and Maekawa (2002), for the given RC column shown in Figure 4, the longitudinal reinforcing bars are expected to undergo a mode 3 buckling (corresponding to a  $L/D=12$ ). However, to conduct a parametric study, all the possible buckling scenarios are considered, i.e. from the best case scenario (buckling span=single tie spacing; i.e.  $L/D=4$ ) to the worst case scenario (buckling span=5 tie spacing; i.e.  $L/D=20$ ). Further, to obtain a global response that is independent of the element size, all the



material models were regularised prior to conducting numerical analysis (Coleman and Spacone 2001). Figure 5 shows the typical material model used in this study along with the fatigue material constant obtained using the proposed fatigue model.

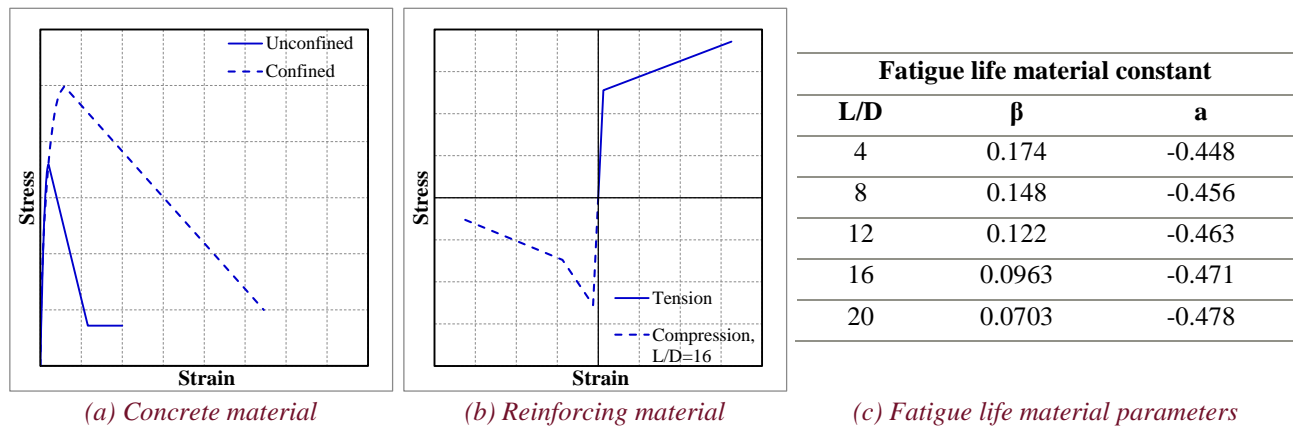


Figure 5: Material parameters for the numerical analysis

Further, the developed numerical model is adopted and parametric studies are carried out to investigate the effect of proposed fatigue model (that includes detrimental effect of buckling) on hysteretic behaviour of RC column. The parametric studies are carried out in two phase, the first phase investigates the effect of fatigue life model on cyclic response of RC column, whereas the second phase investigates the combined effect of buckling and low-cycle fatigue on deformation capacity of RC column.

### 3.1 Effect of low-cycle fatigue model on deformation capacity of column

To investigate the effect of the proposed fatigue model on deformation capacity of a typical RC column, all modelling parameters (size of element, loading history, and material constitutive relations) were kept constant and only the fatigue life coefficient was changed. The fatigue life coefficients for a given bar type were calculated using the fatigue life model (i.e. Equations 4 and 5). It should be noted that to exclude the effect of buckling on hysteretic response of the column, the compressive stress degradation due to buckling was not modelled at this stage. Figure 6 shows the comparison of hysteretic response of RC columns with different bar buckling length. It can be seen from the figure that, as the slenderness ratio of reinforcing bars increases from 4 to 20, accumulation of the cumulative damage in reinforcing bars is accelerated resulting in the column to lose its load carrying capacity at relatively smaller drifts.

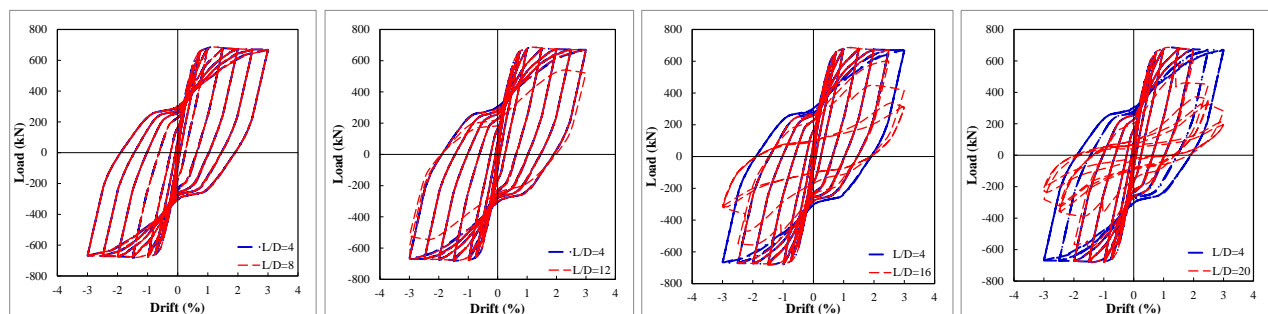


Figure 6: Hysteretic response of RC column including the effect of fatigue

### 3.2 Combined effect of buckling and low-cycle fatigue on column's deformation capacity

To investigate the combined effect of buckling and fatigue on hysteretic behaviour of the RC column, non-linear analyses are carried out with two different axial load ratios of 15% and 30%. A higher level of axial load (with an axial load ratio of 30%) was selected to accelerate the compression damage in the column which

alongside the proposed fatigue model can significantly alter column's deformation capacity. Figure 7 and Figure 8 show the hysteretic response of the column subjected to an axial load ratio of 15% and 30%, respectively. Table 1 summarises the failure drift predicted by the numerical model. As it can be inferred from the figure and table, the presence of buckling and fatigue model significantly accelerated the damage accumulation in the column. Increment in slenderness ratio of reinforcing bar from 4 to 20 resulted a significant reduction in deformation capacity of column. In addition to the reduction in deformation capacity, reduction in energy dissipation due to more pronounced pinching is also observed.

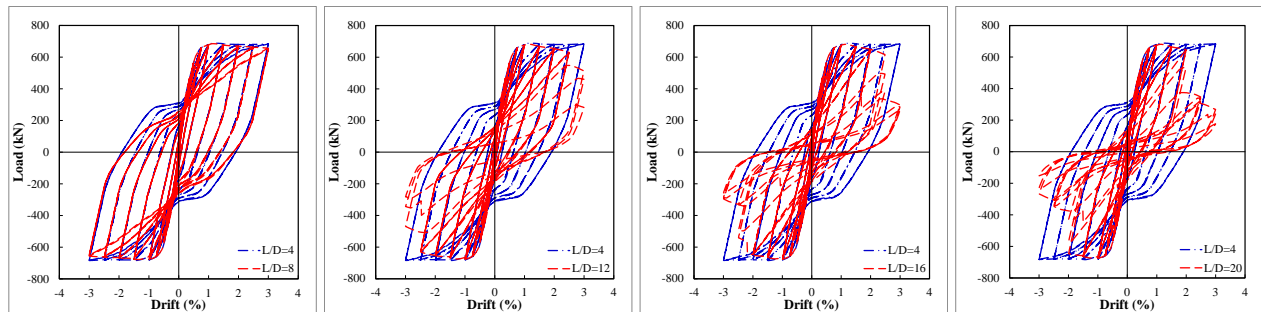


Figure 7: Hysteretic response RC column including the effect of inelastic buckling and fatigue (ALR=15%)

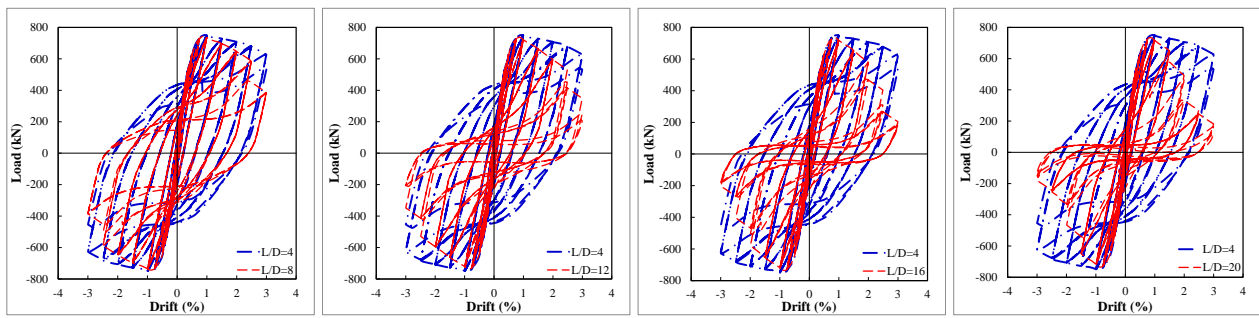


Figure 8: Hysteretic response RC column including the effect of inelastic buckling and fatigue (ALR=30%)

Table 1: Summary of the numerical analysis

(L/D)	Case-1	Case-2	Case-3
4	-	-	2.5%
8	-	-	2.0%
12	2.5%	2.5%	2.0%
16	2.5%	2.0%	1.5%
20	2.0%	1.5%	1.5%

Case-1: Fatigue without compressive stress degradation (ALR=15%)

Case-2: Fatigue with compressive stress degradation (ALR=15%)

Case-3: Fatigue with compressive stress degradation (ALR=30%)

Furthermore, to investigate the effect of buckling on fatigue life of the RC column, constant drift cycles are applied to the model. Here, fatigue life of the column is defined as the number of constant drift cycles that the column can sustain before witnessing bar fracture. Drift levels of 1%, 1.5%, 2%, 2.5%, 3%, and 3.5% are used and repeated drift cycles are applied until the reinforcing bars fractured. A summary of the results obtained from the numerical study is reported in Figure 9. As it can be inferred from this figure, at a given drift level, increase in slenderness ratio of bars causes a significant reduction in fatigue life of the RC column. For instance, when the slenderness ratio of the bar was increased from 4 to 20, the fatigue life of the column (i.e. the number of cycles prior to bar fracture) was reduced by 93% (on average) for all the investigated drift levels. This significant reduction in the remaining life of RC column with change in slenderness ratio of reinforcing bars highlights the importance of the proposed fatigue life model (that includes the effect of buckling) while estimating the residual life or capacity of RC structures. Ignoring the effect of buckling on fatigue life can result in significant overprediction of RC members' remaining life.

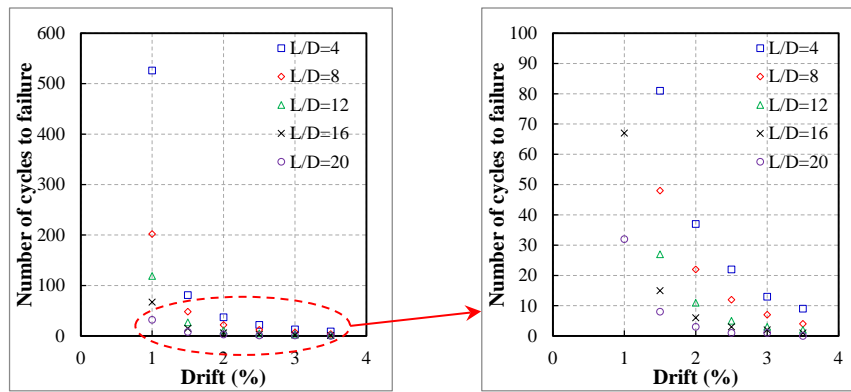


Figure 9: Effect of buckling on deformation capacity of RC column

## 4 CONCLUSIONS

In this paper, the results of an experimental campaign carried out to investigate the effect of buckling on low-cycle fatigue behaviour of reinforcing bars is summarised. The details of the proposed generic low-cycle model that incorporates the effect of inelastic buckling is also reported. Further, the fatigue life model is implemented into the finite element analysis program OpenSees and the combined effect of buckling and low-cycle fatigue life on the seismic performance of a typical RC column is investigated. The major conclusions drawn from the study are:

1. As the buckling length of reinforcing bars increases, their low-cycle fatigue life reduces substantially. For a given grade of reinforcing bars, increase in slenderness ratio of bars resulted a considerable reduction in their low-cycle fatigue life. In addition to this, increasing the yield strength of reinforcing bars (from 300E to 500E) made them susceptible to buckling and resulted in further reduction of the fatigue life.
2. Buckling accelerates strength and stiffness deterioration in reinforcing bars. In buckling prone reinforcing bars (bars with slenderness ratio greater than 6), considerable loss in their tension and compression capacity was noted.
3. A low-cycle fatigue life model relating the total strain amplitude with the fatigue life of reinforcing bars as a function of buckling parameter is developed, which can be implemented in prediction of residual life/capacity of RC structures.
4. Ignoring the effect of buckling on low-cycle fatigue life of reinforcing bars resulted in over-prediction of the deformation capacity of the simulated RC column. For a change in slenderness ratio of the longitudinal bars from 4 to 20, a 93% reduction in fatigue life was observed.
5. The proposed fatigue model alongside a reliable buckling model can reliably predict the deformation capacity of RC columns. The proposed fatigue model is readily available to structural engineering community for non-linear analysis of RC structures.

## 5 ACKNOWLEDGEMENT

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